**Whitepaper for the AAAC Exoplanet Task Force**

# A single-mode nulling coronagraph for ground based imaging of young extrasolar-planets

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## 1. INTRODUCTION AND OVERVIEW

We present a new method to conduct very high contrast near infrared observations of the close environment (i.e. within 15 to 200 mas) of nearby astronomical targets using a single-telescope. This approach, best described as ***single-mode nulling coronagraphy (a.k.a. "fiber nulling")***, uses destructive interference between two or more sub-apertures of a single telescope, in conjunction with fast aperture rotation (~0.1Hz) and wavefront filtering through single-mode fibers. The single-mode filtering approach is key to obtaining a high dynamic range, both in the lab and on ground based telescopes. Indeed, a simple laboratory experiment quickly provided $10^6$ visible laser light cancellation, and over $10^4$ broad-band dual polarization stable rejection around 1.65 microns. A first near infrared set-up will be mounted on the Palomar Hale 5m telescope using two 1.5m sub-apertures in May 2007. In the K band for instance, this initial instrument should provide an angular resolution of ~30 mas (50% transmission point), with an expected contrast ratio > 500:1 on bright targets ($m_K$ <4). We also discuss performance enhancements using differential imaging and active fringe tracking on a large ground based telescope equipped with extreme adaptive optics and located in a prime astronomical site. In that case, ***contrast ratios greater than $10^4$ should be accessible within 15mas*** of the central star, showing that the instrument clearly occupies a unique region between regular coronagraphs, limited in spatial resolution (no high contrast within 100 mas), and long baseline interferometers, traditionally limited in dynamic range (<100:1).

The astrophysical applications of such a device are numerous, ranging from the study of stellar atmospheres and faint debris disks, to the direct detection of brown dwarfs or self luminous planets within a few AUs of young nearby stars. It is the latter application that we emphasize here. We show in particular that an optimized ground based single-mode nulling coronagraph installed on a 5-10 m telescope can conduct an unprecedented census of giant exoplanets around 50 or more nearby (<50pc) young (~1 to 100 Myr) stars. This survey would help assess the fraction of young stars having giant planets in their very inner environment (within ~0.3 to 5 AU), give new information about the time needed to form gas giants around these stars, and help constrain atmospheric/chemistry models in the near infrared. It is worth noting that nearby young stars are generally too active for RV searches, constitute too small a sample for transit searches (not mentioning the variability issue), and can not be observed with the same dynamic range by other direct ground based imaging techniques. Finally, a similar single-mode nulling coronagraph could equip a moderate size (~2m) space telescope and reach even better detection limits. It is described in the white paper by Pravdo et al.: "Finding Exoplanets around Old and Young Low-Mass Stars".

## 2. SCIENCE OBJECTIVES

There are essentially 3 types of science targets for the fiber nuller: spectroscopic binaries, circumstellar disks, brown dwarfs, and planets orbiting nearby young stars. In each case, the ability to achieve magnitude differences $\Delta m_H$ or $\Delta m_K$ of ~10 at only 15-20 mas from the optical axis opens up a whole new class of possible investigation and characterization. We concentrate here on the latter targets type.

The interest in searching for brown dwarfs and planets around young stars (say 10 to 100Myr) has long been understood. In these young systems, the companion's infrared flux is set by internal formation heat rather than by thermal equilibrium with the host star. As a result, their thermal flux is independent of the distance to the star, theoretically allowing very favorable contrast ratios, even far from the star. As a representative example, the predicted flux ratio is about $10^{-4}$ in H and $2x10^{-4}$ in K for a $5M_J$ 10Myr old planet in a 5AU orbit around a K8V star (Saumon et al. 1996). The case of irradiated planets in closer orbits (within 1AU) could be even more favorable (Barrafe et al. 2003). In the late 1990s the TW Hydrae Assocation, the Tucana/Horologium Association, the β Pictoris Moving Group and the AB Doradus Moving Group were identified within ~60pc of Earth, and the η Chamaeleontis cluster was found at 97 pc. These young groups (ages 8-50Myr), along with other nearby, young stars, will enable imaging and spectroscopic studies of the origin and early evolution of planetary systems. Most of these stars are at very negative declinations, showing that observations from the south hemisphere would be optimum. However a reasonable fraction of the stars identified as co-moving with the β Pictoris (~ 12 Myr old) and AB Dor groups (~ 50 Myr old) are north of the ecliptic, so one could still conduct a reasonable survey from northern latitudes. In addition, there are about 50 extra nearby stars (<30pc) observable from the Northern hemisphere and which show Li excitation lines at the Pleiades level or higher (Wichmann et al. 2003), indicating a maximum age of 100Myr or so. The bulk of these young nearby stars have K band magnitudes between 4 and 7, making them prime candidates for the fiber nuller.
So far no program has reported any detection of young planets around these stars, except the possible detection of a ~$5M_J$ companion orbiting 55 AU away from a brown dwarf of the TW Hydrae Association (~ 8Myr old), a very peculiar and interesting case (Chauvin et al. 2004), and the debated detection of a massive planet 0.7" away from the ~1Myr old T Tauri star GQ Lup (Neuhauser et al). Using the VLT NACO instrument, Masciadri et al (2005) concluded that none of their 28 observed young stars had $5M_J$ planets at distances larger than 65 AU. But all the programs of direct detection around these stars use traditional AO assisted coronagraphy, and are only sensitive to quite large separations (>0.5"). The fiber nuller would clearly allow extension of this search to unprecedented levels of angular resolution, reaching inner working distances of the order of 15 mas (λ/4B in H assuming a 6m baseline), i.e. 0.3 AU at 20 pc. The distribution of known exo-planet separations clearly peaks in the inner few AUs, a result evidently biased by the current most successful methods used for planet detection, but that still shows the existence of massive planets in the immediate vicinity of main sequence stars. The fiber nuller could examine the validity of this result for young stars, basically inaccessible to other ground based techniques (transits, RV, and lower performance coronagraphy). Such observations would also give information about the time needed to form gas giants around these stars, check their atmospheric models in the near infrared, and assess the fraction of young stars having giant planets in their very close environment (within ~0.3 to 5 AU).

## 3. PRINCIPLE OF OPERATION

Coming from the sky, the basic components of the rotating single-mode nuller are:

Telescope → AO → "K mirror" → Mask → Nulling BC → SM Fiber(s) → Detector

The "K mirror" (a set of 3 mirrors operating as a pupil rotator) located downstream of the adaptive optics (AO) system delivers to the nulling combiner a beam stabilized in direction. A small fixed pupil mask defines 2 or more sub-beams that trace back to large sub-apertures of the telescope's primary mirror which slowly rotate as the K mirror rotates (at typically 0.1Hz). A variety of well qualified (multi-axial or co-axial) beam combiners (BC) can then be used for nulling, as discussed hereafter. In any case, the output of the BC is focused onto a single-mode fiber, possibly dispersed, and detected. At a given wavelength, the signal from an off-axis source is modulated as the baseline rotates, while the central star remains at null. The single-mode fiber nuller can then truly test and take advantage of the principle of baseline rotation, proposed for the TPF-I and DARWIN space missions (Beichman et al. 1999, Leger et al. 1996). Interestingly, with our system, the baseline rotation is produced by a small pupil rotator. The signal from off-axis sources can then be modulated much faster than in the case of separate telescopes, making the observables more robust against common biases and long term drifts.

The main advantage of the single-mode coronagraph approach lies in the fact that it can achieve a much higher dynamic range than other conventional coronagraphs, and obtain it closer to the optical axis than any other technique.
The first property comes from a well known characteristic of single-mode fibers. They translate wavefront aberrations into amplitude defects, which have a much lower impact on the accessible null or dynamic range. This has been clearly demonstrated in the laboratory, where $10^6$ rejection levels were achieved in the visible (Martin et al. 2003) in the presence of optical aberrations which otherwise limited the performance to 50:1 levels. From a theoretical point of view, one can show (Mennesson et al. 2002) that when single-mode fibers are used, the spatial phase variance of the individual beams only has a second order effect on the null. The achievable contrast ratio goes as $1/\sigma^4_\phi$ and no longer as $1/\sigma^2_\phi$, allowing one to reach high contrast ratios without any stringent requirements on the wavefronts. Very high coronagraphic performance is then possible even with the standard near infrared Strehl ratios (~50-70%) of large ground based telescopes. To first order, the instantaneous null depth – i.e. the accessible dynamic range- is set by the optical path difference (opd) *between* the beams. The ultimate null level is fixed by the variance of this opd over the individual integration time. For bright targets (~$m_H$ or $m_K$ <5), this integration time can be chosen small enough to freeze the phase fluctuations and statistically reach very deep nulls (~1e-4 or less). More details on the expected sky system performance are given in section 4.
Deep levels of rejection can then be achieved in the near infrared, where one can take advantage of the high spatial resolution and access the same resolving power as Keck-I or the LBTI in the thermal infrared. But this can now be done with at least 10 times better dynamic range, a better ability to detect point sources (baseline rotation), and without the complexity inherent to the operation of ground based interferometers and mid-infrared observations. In the fiber nuller case, the angular resolution is set by the *distance* B between the telescope sub-apertures. It is then

comparable to the diffraction limit of the telescope, or even better considering that the first constructive peak is located at λ/2B, and that 50% transmission occurs at λ/4B, i.e. 16 mas for a 5m sub-aperture separation and observing in the H band.

## 4. BEAM COMBINATION

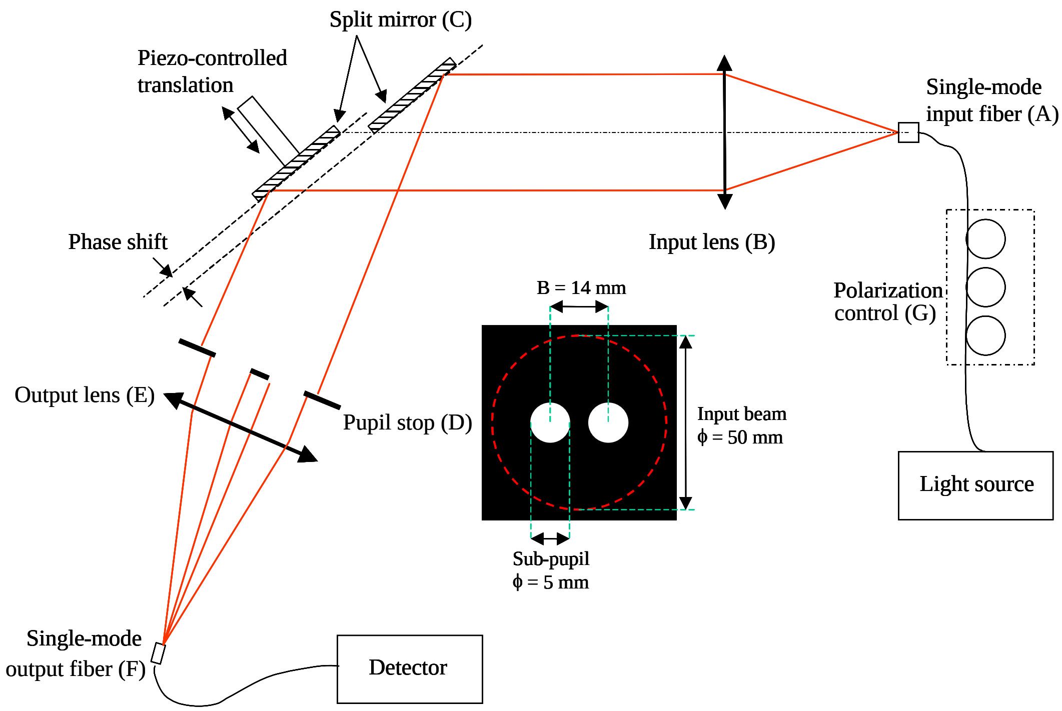



Figure 1: Fiber nuller set-up tested in the laboratory (multi-axial recombination case) and similar to the initial system to be implemented on Palomar.

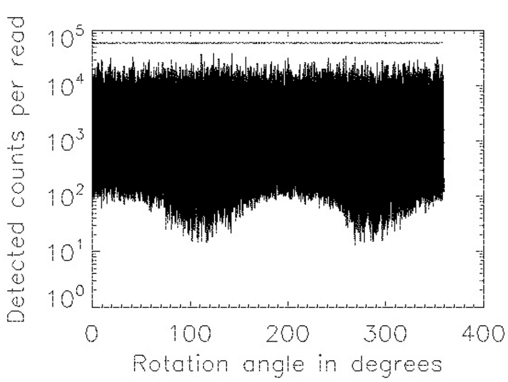
There are two means to interfere beams coming from separate apertures or sub-apertures: co-axial and multi-axial beam combiners (BC). While co-axial BC are more widely used and have been well characterized for nulling applications, using aperture flips (Wallace 1999, Martin 2003) or dielectric plates (Mennesson 2003), multi-axial fiber nulling is arguably the simplest way of interfering two beams destructively, and the easiest system to install on a telescope. Its principle is now well known (Serabyn 2003) and presented on figure 1 in our initial lab set-up. A mask with 2 holes is used to define two beams from a single collimated beam. In the case of LASER light nulling, a λ/2 opd step, i.e a π phase shift, is generated between the two beams using a split mirror. The beams are then focused on a single-mode waveguide whose output end is imaged onto a detector. In that sense, together with the fiber, it is simply the focusing element (lens or off-axis parabola) that provides the beam-combination. When the beams are interfered with a pi phase shift, the distribution of the electric field in the focal plane is asymmetric, crossing zero and changing sign on the optical axis. The waveguide mode being symmetric, no energy is coupled into the fiber. The multi-axial fiber nuller is well suited to the case where several sub-apertures need to be properly phased and recombined all together. Although advantageous for their simplicity of operation and ability to recombine many beams together, multi-axial BCs may not be a panacea in all cases. They are less sensitive than co-axial schemes (lower coupling efficiency to the fiber, even after densification) and are not easily applicable to the case where many pairs of sub-apertures (e.g. with different baseline lengths and orientations) are to be recombined, and nulled through different fibers.

## 5. MODELING OF SYSTEM PERFORMANCE

We discuss here three cases, analyzing the expected performance of an initial “minimal” set-up to for the Palomar 200 inch telescope (to be tested this year), an upgraded ground based system on a large telescope, and a possible space instrument.

***Palomar set-up (to be tested in 2007/2008, first run: May 2007)***

Our initial performance modeling is for K band (~2.2 microns) observations with a multi-axial fiber nuller operating behind the current Palomar AO system (layout similar to fig.1, but with additional angle tracking and achromatic phase shifters). Simulations using two 1.5m diameter sub-apertures located 3.5m apart show that such a system should detect faint companions at the 500:1 limit as close as 40 mas from the optical axis. Figure 2 shows a simulation of the broad-band K signal detected using this set-up and observing an mK=3 star with a 500 times dimmer companion located either 40 mas (a) or 180 mas (c) away. In both cases, the residual piston between the two sub-apertures is 150nm rms (consistent with 180nm rms for the full aperture after AO) with a Kolmogorov Power Spectral Density above 30 Hz. The strehl ratio of the individual sub-apertures is 70% +/- 5% rms, the camera read out noise is 10e- rms, the thermal background is 1.3 $10^3$ ph/s. The horizontal axis refers to the rotation angle of the baseline. Each point represents the signal measured for each rotation angle, over 60 successive rotation cycles, each turn taking 5 seconds. The read-out-time is 10 ms, or 500 reads per turn.



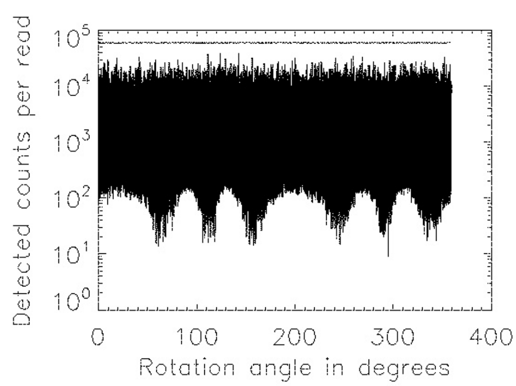




Figure 2: Simulated performance on the Palomar 200 inch in K band. Left: Null signal obtained from a magnitude 3 star with a 500 times dimmer companion 40mas away. All noise sources included. Top line indicates the constructive signal. Right: same but for companion 180 mas away. Note the distinctive higher harmonics.

An important point is that although the opd rms (over long timescales) is 150nm, limiting the average null depth to about $10^{-2}$ in K, it is statistically possible to measure much deeper nulls with high signal to noise over short integration times. Companions are clearly detected in the two nulling sequences of fig.2: as the baseline is perpendicular to the star / companion direction, very deep nulls are achieved, and statistically significant. Conversely, when the off-axis companion is constructively interfering, the nulls can not exceed the brightness ratio between the two sources.

***Ultimate ground based performance***

As stated above, the average null level is set by the mean opd rms over long timescales, while the highest accessible contrast ratio is primarily set by the residual opd variance over the unit integration time. This ultimate null level can be improved in one of two ways: 1) lowering the unit integration time, 2) calibrating the null degradation due to opd. The first point, a matter of sensitivity, can be addressed by using larger or more numerous sub-apertures, more efficient beam combination schemes, low noise detectors and lower background levels. Simulations show that using two 3m diameter apertures which are 5m apart and observing a magnitude 5 star in the H band with a low noise camera, ***companions at the 1e-4 level can reliably be detected at only 15mas*** from the optical axis. The second point is addressed by ***differential nulling*** between nearby wavelengths (e.g in the H band). This is similar to the differential imaging approach (but now subtracting the 1$^{st}$ order of optical aberrations: opd) – using filters in and out of strong methane absorption lines in the atmospheres of cold brown dwarfs and young giant planets. One can reasonably expect another 10fold performance improvement via this method, setting the ultimate ground based dynamic range to ***~1e-5*** or better with a near infrared fiber nuller.

***Performance of potential space based instrument (see whitepaper by Prado et al.)***

More simulations are necessary to study this option. But in the absence of atmospheric phase fluctuations, and within the quiet environment of space, it is expected that longer integration times can be used without accumulating large opd drifts, so that better null depths and /or dimmer targets can be accessed.

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## 6. TECHNOLOGY STATUS AND FUTURE MILESTONES

Co-axial nulling interferometry using single-mode fibers has been tested successfully in the lab over a wide range of wavelengths and using a variety of techniques. All of these techniques have reached broadband (15% or more) null depths of 1e-4 or less. Similar results have been recently

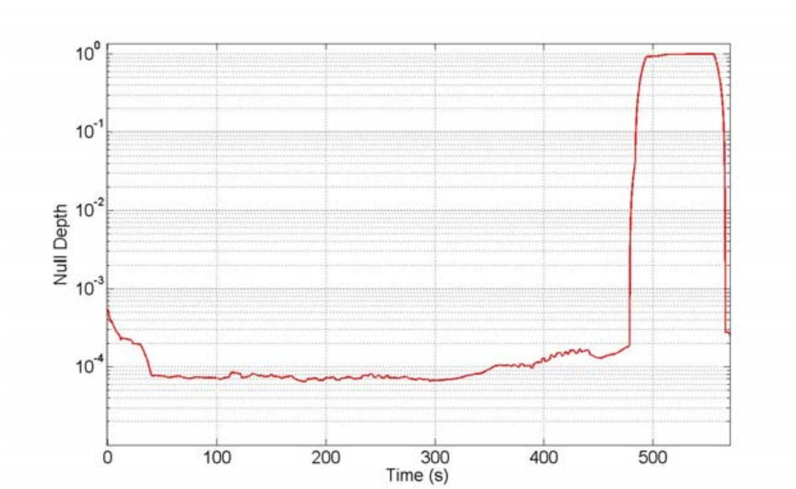


Figure 3: Null depth vs time obtained with fiber nulling set-up presented in figure 1 (with additional dispersive plates). Dual polarization broadband nulls (1.5 to 1.8 microns)

obtained by our group using multi-axial nulling interferometry, proving the feasibility of the technique. Visible light laser nulls of the order of 1e-6 have been obtained in 2005 (Hagenauer and Serabyn), while stable <1e-4 broad-band near infrared nulls quickly followed (Mennesson et al. 2006, and in prep.), as shown in figure 3. The next milestone is to operate a K band fiber nuller at the Palomar 200" telescope over 2007-2008. The goal is to demonstrate the system's ability to get deep broad-band nulls (~1e-3) and reliably detect faint companions (<1e-2 of primary) over separations ranging from ~30 to 200 mas. After this initial sky demonstration, we plan to implement various upgrades to provide increasing performance over time. This includes fringe tracking, spectral differential nulling employing a high-sensitivity rapid-read-out camera, and moving to a large ground based telescope equipped with an extreme AO system, potentially located in the southern hemisphere where a larger fraction of nearby young stars are observable.

## 7. PRESENT FUNDING / FURTHER POTENTIAL DEVELOPMENTS

Our initial fiber nuller work is currently funded through two small grants which aim at demonstrating the basic physics of faint neighbor detection using this technique. This fairly simple technique has a unique potential in terms of accessible spatial resolution (~15mas) and contrast (>$10^4$) for the census of nearby faint companions in the near infrared. It truly promises to bridge the gap between interferometers, so far limited in dynamic range (~100:1) and traditional coronagraphs which only access high contrast at large separations (a few 100 mas). Our next step is to turn our initial set-up into a PI-class instrument installed at a prime astronomical site, for which larger budgets will be needed. An optimized ground based system can also serve as a scientific and technological precursor to a future space based coronagraph (see whitepaper by Pravdo et al.) and for both flavors of TPF.

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